Microwave Analog Fiber-Optic Link for Use in the Deep Space Network

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A novel fiber-optic system with dynamic range of up to 150 dB-Hz for transmission of microwave analog signals is described. The design, analysis, and laboratory evaluations of this system are reported, and potential applications in the NASA/JPL Deep Space Network are discussed.

I. Background and Introduction

Commercially available fiber-optic links for microwave analog signal transmission do not meet the most stringent dynamic-range requirements for use in the NASA/JPL Deep Space Network (DSN). At present, the performance of the fiber-optic transmitters limits the capacity of these links. Although semiconductor-laser-based fiber-optic systems are commercially available with frequency response to 10 GHz [1], the output power, intensity noise, and modulation linearity of the semiconductor laser sources limit system dynamic range to about 125 dB-Hz [2]. While this may be adequate for many applications, it falls short of the most stringent requirements of the DSN (which will be discussed in detail below), where dynamic range on the order of 150 dB-Hz is required.

The dynamic range of a fiber-optic system is determined by the optical power, the modulation depth, and the noise floor. Commercially available microwave fiber-optic transmitters employ semiconductor lasers with optical power typically 1–3 mW. Intensity modulation is achieved by direct modulation of the bias current with the radio frequency (RF) or microwave signal. The linearity of the laser typically limits modulation depth to less than 50 percent, before harmonic distortion becomes too great. Semiconductor lasers exhibit a pronounced amplitude noise increase at microwave frequencies. Therefore, the dynamic range possible for microwave fiber-optic systems is limited by laser power, modulation depth, and laser intensity noise to approximately 125 dB-Hz.

To increase dynamic range, one or all of the following must be done:

(1) Increase the optical power

(2) Increase the modulation depth

(3) Reduce the system noise floor

Commercial manufacturers of microwave fiber-optic transmitters have attempted to maximize all three of these parameters, but still are 25 to 30 dB away from the maximum dynamic-range requirements of the DSN.

Another way to achieve extreme levels of dynamic range (> 150 dB) in a fiber-optic system is by external intensity modulation of a high-power, low-noise laser source.

Until recently, reliable and field-worthy solid-state lasers did not have adequate power and low-enough-intensity noise to make such a system feasible. External intensity modulators were available, but had high excess optical loss. This made construction of a field-worthy system infeasible, since impractically high power levels would be required to offset the optical losses.

Recent advances in all-solid-state high-power, ultralow-noise, narrow-linewidth diode-pumped neodymium : yttrium-aluminum-garnet (Nd:YAG) lasers and microwave optical modulators with low insertion loss were recognized by the authors as possibly providing the building blocks for a system which approaches the dynamic range and bandwidth performance levels required in the DSN. Recent tests of the key components and the following analysis confirm that such a system is feasible at this time.

In order to extend the performance of the frequency-reference distribution systems already in place, and to address new applications for fiber optics in the DSN, a novel fiber-optic link for RF and microwave analog signal transmission was designed, analyzed, constructed, and tested. This system offers extremely high dynamic range of 150 dB-Hz (150 dB in a one-hertz bandwidth) with frequency response to 18 GHz from commercially available components. The system employs intensity modulation of a high-power, low-noise solid-state Nd:YAG laser with a lithium niobate ($LiNbO_3$) electro-optic modulator, an improved type of single-mode optical fiber with low thermal coefficient of delay (TCD), and a commercially available optical receiver.

This article describes the design of the link, and the calculated and measured performance of the two key components: the intensity modulator and the Nd:YAG laser. The expected dynamic range of a fiber-optic system employing these components is then predicted with a system model. Two Nd:YAG lasers and a modulator were loaned to JPL for evaluation by the manufacturers. A laboratory-bench fiber-optic link was constructed from these components. Measurements performed on this link match the predictions of the model. Next, the reliability of the various components is discussed, and various applications of these links in the DSN are examined.

In particular, a study of the suitability of such a fiber-optic link for the transmission of the S-band (2.4 GHz) and X-band (8.4 GHz) outputs of the low-noise amplifiers of DSN antennas to a remote signal processing center (SPC) is summarized. The delay stability possible with such a link using a new type of temperature-compensated low-TCD fiber is illustrated by a calculation. Finally, remaining questions and ongoing research efforts are discussed.

II. Fiber-Optic System Design

In the course of development of ultrastable fiber-optic systems for precise frequency-reference signal distribution, the authors have recognized that recent developments in opto-electronic component technology now make feasible the construction of a microwave analog fiber-optic system with the following desirable characteristics:

(1) High dynamic range, up to 150 dB-Hz

(2) Frequency response to 18 GHz now, and higher in the future

(3) Low intermodulation distortion

(4) Low group-delay distortion

(5) High group-delay stability, $<$ 1 picosecond over intracomplex distances

(6) High reliability

Such a system is now feasible due to recent technological advances of the following key components:

(1) Optical sources: semiconductor, laser-diode-pumped, solid-state lasers with high output power, narrow-linewidth single-frequency operation, and extremely low noise

(2) Optical intensity modulators: wide frequency response (to 18 GHz), low optical insertion loss

(3) Low thermal coefficient of delay (TCD) optical fiber

A block diagram of the proposed fiber-optic system is shown in Fig. 1. A semiconductor-laser-diode-pumped solid-state Nd:YAG laser generates the optical carrier at 1318.5 nm. An optical isolator prevents reflected optical power from entering the Nd:YAG laser, since reflected optical power destabilizes the optical output. After the isolator, an electro-optic modulator intensity-modulates the optical carrier with the electrical microwave signal. A single-mode low-TDC optical fiber carries this modulated optical signal to an optical receiver which converts the optical signal back to the original electrical microwave signal.

Questions remain about the phase and amplitude linearity of the electro-optic modulators in the passbands of interest (S- and X-band) for the DSN. There were not sufficient time and equipment to fully characterize these parameters with the borrowed components. However, it is felt that adequate performance can be achieved over the narrow frequency bands used by the DSN with proper microwave matching of the electro-optic modulator to the signal source. This option is currently being investigated.

III. Diode-Pumped-Nd:YAG Lasers

Two samples of the semiconductor-laser-diode-pumped Nd:YAG lasers were loaned to JPL by two manufacturers: Amoco Laser (Naperville, Illinois) and Lightwave Electronics (Mountain View, California). The Amoco laser is an end-pumped linear-cavity type which lases in two longitudinal modes. The Lightwave laser employs a novel nonplanar ring cavity which exhibits true single-mode operation. The output power of both lasers was advertised to be 25 mW at 1318.5 nm; each laser slightly exceeded the output power specification.

The noise performance of these lasers was tested and found to be shot-noise limited. For a shot-noise-limited system, the noise power spectrum is white (flat with frequency), and depends on the optical power level [2]:

$$P_{\text{shot}} = 2eI_oR_L \quad (\text{W/Hz}) \tag{1}$$

where

$$I_o = rP_o10^{-(P_L/10)} \quad (\text{A}) \tag{2}$$

is the average photocurrent induced by the incident laser power, r is the responsivity of the photodiode in amps per watt, P_o is the optical output power of the laser in watts, P_L is the optical loss between the laser and photodiode in optical dB, e is the electronic charge, and R_L is the load resistance.

The noise was flat in frequency with the exception of a slight hump at about 300 kHz due to the relaxation resonance of the laser cavity. This noise was 3 dB higher than the shot-noise floor for the Amoco laser, and was found to vary substantially in amplitude as a function of back reflections for the Lightwave laser. The use of a 35-dB optical isolator, a routine engineering solution, was found to eliminate the effects of optical reflections on the laser output.

In an actual system, shot noise will predominate until the optical losses become high and the thermal noise of the receiver becomes significant. The total noise power as a function of optical loss is

$$P_{\text{noise}}(P_L) = P_{\text{shot}}(P_L) + P_{\text{th}} \quad (\text{W/Hz}) \tag{3}$$

where P_{th} is the thermal-noise power. For a matched load, this is

$$P_{\text{th}} = kTF \quad (\text{W/Hz}) \tag{4}$$

where k is Boltzmann's constant, T is the temperature in kelvins, and F is the noise figure of the amplifier following the photodiode.

IV. Electro-Optic Intensity Modulators

Electro-optic (E-O) modulators suitable for use in high-dynamic-range fiber-optic links have recently become available. These modulators have good linearity, with less than 5 percent total harmonic distortion at 80 percent modulation index. At present, the modulation bandwidth is as high as 18 GHz.

Waveguide versions of the Mach-Zehnder interferometer E-O modulator provide the highest modulation frequency response for use in fiber-optic systems [3]. The interferometer is fabricated by diffusing titanium into high-purity lithium niobate substrates to form optical waveguides.

The E-O modulator consists of an input optical waveguide which splits into two parallel waveguides located under a metallic microwave-transmission line. The dielectric for the microwave transmission line is the lithium niobate substrate, which contains the optical waveguides. After passing under the microwave transmission line, the two optical waveguides converge to form a single optical waveguide which exits the device.

Modulation is accomplished by generating a difference in delay between the optical signals traveling in the two parallel optical waveguides. The electric field of the microwave signal changes the dielectric constant of the lithium niobate via the linear electro-optic (Pockels) effect. A change in the dielectric constant of the optical waveguide results in a change in propagation velocity and therefore a change in delay of the optical signal. When the two optical signals are added back together in the output optical waveguide, interference between the two signals results in an amplitude-modulated optical output signal. If the two optical signals which are combined in the output waveguide are in phase, they add in power. If they are out of phase, they cancel and no power exits the device.

Since the delay change in the waveguide is linear with voltage, there is a linear change in the phase difference between the two optical signals, which are then added vectorially. This results in a well-defined cosine-squared intensity-modulation response.

Figures 2 and 3 illustrate the calculated modulation response for single-tone modulation of various indices, and the calculated FFT (fast Fourier transform) of the response. Since the modulator response is symmetric, the even harmonics are theoretically zero. From Fig. 3, at 81 percent modulation, the third and higher harmonics are down more than 28 dB below the fundamental, corresponding to less than 5 percent total harmonic distortion (THD) for the highest level of input signal.

The linearity of a modulator manufactured by GEC-Marconi, and loaned to JPL by Hoechst Celanese was tested by measuring the harmonic content as a function of modulation index. The measured results match the theoretical predictions extremely well: modulation depth of 80 percent was achieved with third harmonics more than 28 dB below the fundamental. Second harmonics were down better than 50 dB, but were strongly influenced by the biasing of the modulator, as expected.

V. Model for Dynamic-Range Predictions

The Institute of Electrical and Electronics Engineers (IEEE) dictionary defines the dynamic range of a communications system as the ratio of the saturation signal level to the minimum acceptable signal level. This is the definition we shall use. The saturation signal level is set by the maximum acceptable level of harmonic content. We shall take the minimum acceptable signal level to be equal to the equivalent input noise (EIN) of the fiber-optic link.

The dynamic range is thus the ratio of two signal levels at the link output: (1) the output signal level produced by an input signal equal to the saturation level of the optical modulator, and (2) the noise floor at the output. The output signal level for a given input level is calculated using standard formulae for amplitude-modulated fiber-optic systems [2]. The radio frequency (RF) signal power out of the fiber-optic system is a function of the modulation index and the optical losses:

$$P_{\mathrm{rf}}(P_{\mathrm{L}}) = 1/2[mr]^2[P_{\mathrm{o}}\ 10^{-(P_{\mathrm{L}}/10)}]^2 R_{\mathrm{L}} \tag{5}$$

where

$m =$ the optical modulation index

$r =$ detection efficiency of the photodiode (responsivity)

$P_{\mathrm{o}} =$ the average optical power (at pigtailed laser output)

$R_{\mathrm{L}} =$ the load resistance across the photodiode

The optical loss is

$$P_{\mathrm{L}}\ (\mathrm{dB}) = P_{\mathrm{fixed}}\ (\mathrm{dB}) + P_{\mathrm{fiber}}\ (\mathrm{dB/km}) \cdot L\ (\mathrm{km}) \tag{6}$$

where L is the fiber length in kilometers. The loss consists of fixed insertion losses of the various components in the optical path (P_{fixed}), such as the modulator insertion loss, connectors and splice losses, and P_{fiber}, the variable loss due to the length of the fiber.

For a given input optical power level and maximum modulation index, the dynamic range of the fiber-optic link is a function of the optical losses. The losses increase with fiber length, so the dynamic range decreases:

$$\begin{aligned} D(L) &= 10\log[P_{\mathrm{rf,max}}(L)/P_{\mathrm{noise}}(L)] \quad (\mathrm{dB\text{-}Hz}) \\ &= 10\log[P_{\mathrm{rf,max}}(L)/(P_{\mathrm{shot}}(L) + P_{\mathrm{thermal}})] \quad (\mathrm{dB\text{-}Hz}) \end{aligned} \tag{7}$$

In a high-performance, low-loss system, shot noise would be more significant than the thermal noise, so the system is said to be "shot-noise-limited." Considering the dynamic range when the system is shot-noise-limited, the last equation simplifies to:

$$\begin{aligned} D\ (\mathrm{dB\text{-}Hz}) = 10\ \log[(m_{\mathrm{max}}^2 r)/4e]\ (\mathrm{dB\text{-}Hz}) \\ + P_{\mathrm{o}}\ (\mathrm{dB}) - P_{\mathrm{L}}\ (\mathrm{dB}) \end{aligned} \tag{8}$$

where m_{max} is the maximum acceptable modulation index (limited by the acceptable harmonic distortion level), and as before, r is the photodiode responsivity, P_{o} is the optical power level, and P_{L} the optical loss. From this expression, it is clear that if the maximum acceptable modulation index is fixed, the dynamic range of the fiber-optic link can only be increased by employing a more powerful optical source or by reducing the optical losses. The system assembled in the laboratory had the following parameters:

$m_{\mathrm{max}} =$ 80 percent modulation, corresponding to less than 5 percent THD at the saturation level

$P_{\mathrm{o}} =$ 25 mW (14 dBm) optical power at the laser output

$r =$ photodiode responsivity: 0.4 A/W

$P_{\mathrm{L}} =$ optical loss of the system: 20 dB

This corresponds to a predicted value for the dynamic range of:

$$D = 140.1 \text{ dB-Hz} \tag{9}$$

which agreed extremely well with the observed value. The optical losses in the laboratory system were 10 dB higher than the design levels, due to problems in coupling the optical power into the modulator for lack of the proper optical components. This is not a serious problem, and can be solved with proper optics. If the losses had been only 10 dB, the dynamic range would have been 150 dB-Hz.

This result is significant, however, because it validates the model for dynamic-range predictions. From this simple model, it is apparent that improved performance can be obtained by using a higher power laser, a higher responsivity photodiode, and decreasing the optical losses.

To get an idea of how an actual system would perform, a prediction can be made using the model with values for commercially available components which were not on hand in the lab. Typical single-mode fiber has very low loss: $P_{\text{fiber}} = 0.4$ dB/km. Typical values for the fixed-system optical losses, as measured by JPL, for the various optical components are:

modulator	8	dB at the bias point
2 connectors	2	dB
4 fusion splices	0.4	dB
$\Rightarrow P_{\text{fixed}}$ =	10.4	dB

Lasers with output power of up to 175 mW and photodiodes with responsivities of 0.7 A/W are commercially available. Figure 4 is a plot of the calculated fiber-optic system dynamic range as a function of fiber length for a hypothetical practical system with the following conservative parameters:

(1) A conservative value of $P_{\text{fixed}} = 12$ dB for a typical system fixed optical loss

(2) $P_o = 30$ mW (14.8 dBm) coupled into the modulator

(3) $r = 0.7$ A/W, commercially available photodiode responsivity

(4) $T = 300$ k

(5) $F = 3$ dB, noise figure of the first amplifier

From Fig. 4, it is apparent that system dynamic range of 148 dB-Hz is maintained for distances up to 3.5 kilometers.

The practical upper bound on the optical power level is determined by the saturation-current level of the photodiode in the optical receiver. Commercially available high-speed photodiodes are adequately linear up to about 2 mA of average photocurrent. This corresponds to an incident average optical power level of 1.43 mW = 1.6 dBm for photodiode saturation. For the system modeled in the above calculation with 14.8 dBm optical power at the input to the modulator and a 3.5 km fiber length, the optical losses would be 13.4 dB, so the optical incident power is 1.4 dBm = 1.3 mW, which is within the linear operating range of the photodiode.

Further advances in photodiode saturation levels may enable more powerful optical sources to be used, which will increase dynamic range accordingly. Also, increasing the load impedance, R_L, of the receiver would relax the requirement on optical power, or equivalently, allow shot-noise-limited performance with longer lengths of fiber. This may become possible as lower capacitance, higher speed photodiodes become available, and with improved microwave receiver designs.

VI. Components and Reliability

Most of the devices which would be used in the proposed fiber-optic system have proven reliability performance. PIN photodiodes are known to have mean-time-before-failure (MTBF) of 10^5 to 10^6 hours. There is no known mechanism which would result in early failure of the electro-optic modulator if the modulator were hermetically packaged. Researchers have found no degradation in these devices over time, but extensive reliability testing has not been performed. The lifetime of optical fiber has been estimated to be greater than 100 years if properly protected by the surrounding cable.

The semiconductor-laser-diode-pumped Nd:YAG laser is the least reliable assembly in the proposed system. The lifetime of current lasers of this type is in the range of 5 to 20 thousand hours. However, the manufacturers have not yet addressed the reliability aspects of their designs. There are several approaches that have been suggested to increase the lifetime of these lasers. They are:

(1) Operate the pump laser at a lower temperature

(2) Underrate the pump laser more

(3) Identify a more reliable pump laser and use it

(4) Use multiple pump lasers which are switched in one at a time when the previous laser deteriorates to a predetermined level

A reasonable MTBF (>50,000 hours) should be readily achievable if engineering effort is devoted to this problem.

VII. Fiber-Optic Link Requirements for Low-Noise Amplifier Output Transmission

This section will give the requirements for transmission of the microwave output of the maser and high-electron mobility transistor (HEMT) low-noise amplifiers (LNAs) used in the NASA/JPL DSN. This will be followed by an analysis showing how the proposed fiber-optic links can meet the requirements. Finally, the improvement to system stability by removal of the RF to intermediate frequency (IF) equipment from the cone to a vibration-free, temperature-stable environment will be discussed.

The construction of such a system requires a thorough understanding of the characteristics of the front end of a DSN receiver. In the analysis that follows, the noise temperature and saturation levels of both the maser and HEMT LNAs are used to determine the specifications for a transmission system which can pass these signals without degrading the system-noise temperature.

The front-end of every DSN antenna is composed of either a maser or HEMT low-noise amplifier. The signal levels for each amplifier type are as follows:

Amplifier	Noise Temp./N_o	Saturation Level	Gain
maser	15 K/−186 dBm/Hz	−86 dBm	45 dB
HEMT	30 K/−183 dBm/Hz	−66 dBm	45 dB

The fiber-optic system should ideally be able to handle the worst case of signal extremes for either amplifier. This worst case corresponds to the lowest noise level and the highest saturation level. As indicated above, the maser has the lowest noise floor, while the HEMT has the highest saturation level. Each of the LNAs has 45 dB of gain, so that the noise level at the output of the LNA is −186 dBm + 45 dB = −141 dBm/Hz. The saturation level at the output is −66 dBm + 45 dB = −21 dBm.

The required dynamic range of the fiber-optic system is determined using the data for the LNAs and the IEEE definition for dynamic range discussed previously. The ratio of the saturation level and the minimum acceptable signal level determines the available dynamic range of the front end on a per-hertz basis:

$$P_{\text{sat}}/N_o = -66 \text{ dBm} - (-186 \text{ dBm/Hz}) = 120 \text{ dB-Hz} \tag{10}$$

The equivalent input noise of the fiber-optic system must be sufficiently below the output noise level of the front-end amplifier chain so that the overall system-noise temperature is not excessively degraded. A conservative estimate is that the fiber-optic system input noise must be ≈28 dB below the noise of the amplifier output so that the overall system-noise temperature is degraded by about 0.15 percent. This is much less than the 1 percent maximum acceptable degradation for the whole system.

Also, the fiber-optic system must handle signals up to the saturation level of the LNA. Any signal at this level will already be saturating the LNA, so excessive dynamic range above this level is not required from the fiber-optic system. The maximum drive level of the fiber-optic system is determined by the maximum allowable harmonic content in the signal. For single-tone modulation, system performance with less than 5 percent total harmonic distortion requires that the largest harmonic must be 26 dB below the fundamental tone, with all other harmonics substantially below this level (at least 10 dB). When the LNA reaches its 1 dB compression point, the harmonic content added by the fiber-optic system must be at least 26 dB below the signal level.

These requirements for the fiber-optic system define the dynamic range needed to pass the LNA output signal while degrading the system-noise temperature by less than 0.15 percent. The dynamic-range requirement for the fiber-optic system is:

$$\begin{aligned} D_{\text{FO}} &= P_{\text{sat}} - (N_o - 28 \text{ dB}) \\ &= -66 \text{ dBm} - (-186 \text{ dBm/Hz} - 28 \text{ dB}) \\ &= 148 \text{ dB-Hz} \end{aligned} \tag{11}$$

From Fig. 4, conservative calculations indicate that this requirement can be met with commercially available components for link lengths up to 3.5 kilometers.

The number calculated for D_{FO} applies throughout the 500-MHz bandpass at both S- and X-band. The number is given as a dB-Hz specification to preserve full generality, since individual applications have different bandwidths. To derive the specification for a given application, one only need divide D_{FO} by the bandwidth of the application.

For example, a wideband application employing the full 500-MHz bandwidth of the LNA, such as very longbaseline interferometry (VLBI), would require dynamic range *in dB* of

$$D_{\mathrm{FO-VLBI}} = D_{\mathrm{FO}} - 10\ \log(500\ \mathrm{MHz})$$

$$= D_{\mathrm{FO}} - 87\ \mathrm{dB\text{-}Hz}$$

$$= 62\ \mathrm{dB} \tag{12}$$

for the 500-MHz bandpass. Conversely, a telemetry application may have a 10-MHz bandpass, so the dynamic range required is

$$D_{\mathrm{FO-TLM}} = D_{\mathrm{FO}} - 10\ \log(10\ \mathrm{MHz})$$

$$= 79\ \mathrm{dB} \tag{13}$$

Both applications require the same per-hertz dynamic range, which is fundamentally limited by the LNA. Therefore, if the fiber-optic system can handle the full per-hertz dynamic-range requirement set by the LNA, it will handle any application which currently uses that LNA.

For a two-kilometer link, the system signal and noise levels are as indicated in Fig. 5. The additional gain after the LNA is required to raise the noise level of the LNA above the input noise of the fiber-optic system, but since the LNA has 45 dB of gain, a 3-dB noise figure for this amplifier will degrade the system temperature by 0.1 percent. The level at the output of the fiber-optic system is the same as the level at the output of the LNA when the additional gain equals the insertion loss of the fiber-optic link. This makes the interface to the first mixer transparent, and no additional gain is required before the first mixer.

VIII. Low Thermal Coefficient of Delay Fiber-Optic Cable

Low thermal coefficient of delay (TCD) single-mode optical-fiber cable will be used with a simple form of thermal control to achieve near-zero change in group delay with changes in temperature. This special fiber has a TCD near zero (<0.01 ppm/deg C) between 10 deg C and 20 deg C which increases to 0.4 ppm/deg C at about 35 deg C. The near-zero TCD of the cable over a wide temperature range simplifies thermal control of the cable. If the temperature of the cable is held near 15 deg C, small changes (± 5 deg C) in temperature will have little effect on the group delay.

All of the fibers requiring high thermal stability can be contained in a single cable less than 1 inch in diameter. The temperature of this cable could be maintained near 15 deg C on the antenna by installing it with a chilled liquid line enclosed in insulation. The cable could be buried underground between the antenna and the signal processing center (SPC). The temperature at 1.5 meters depth at Goldstone has been found to be about 10 deg C and stable to millidegrees C.

The change in group delay of a cable is

$$dD_{\mathrm{g}} = [K_{\mathrm{TCD}}(L)dT]/[10^6 V_{\mathrm{g}}] \tag{14}$$

where

K_{TCD} = the thermal coefficient of delay for the cable at the operating temperature in ppm/deg C

L = the length of cable subjected to the temperature change

dT = the temperature change on the cable

V_{g} = the group velocity in the cable

For the cable run between SPC-10 and the Deep Space Station (DSS)-15 antenna, the total group-delay change in the cable as a result of temperature change can be calculated based on the following conservative assumptions:

(1) total cable length of 500 meters

(2) fifty meters of cable in the antenna cooled to 15 deg C (TCD = 0.01 ppm/deg C) and subjected to ± 3 deg C change in temperature

(3) ten meters of cable in the wrap-up at 25 deg C (TCD = 0.12 ppm/deg C) and subjected to ± 5 deg C change in temperature, and

(4) 440 meters of underground cable at 10 deg C (TCD = 0.05 ppm/deg C) and subjected to ± 0.1 deg C change in temperature

The delay instability is evaluated from Eq. (14) for dD_{g}, using the assumed values given for each section of cable. For the antenna section of cable,

$$dD_{\mathrm{g}} = [0.01(50)6]/[10^6(2.1\times 10^8)] = 0.014\ (\mathrm{psec}) \tag{15}$$

for the wrap-up section of the cable,

$$dD_{\mathrm{g}} = [0.12(10)10]/[10^6(2.1\times 10^8)] = 0.06\ (\mathrm{psec}) \tag{16}$$

and for the buried portion of the cable,

$$dD_{\mathrm{g}} = [0.05(440)0.2]/[10^6(2.1 \times 10^8)] = 0.02\ (\mathrm{psec}) \tag{17}$$

The total delay change is the sum of the changes in the three sections,

$$dD_g(\text{total}) = 0.014 + 0.06 + 0.02 = 0.094 \text{ (psec)} \quad (18)$$

This represents a diurnal phase change at 8.4 GHz of 0.34 degrees or 0.006 radians that is contributed by the cable. This corresponds to a fractional frequency deviation of

$$df/f = dt/t = 0.094 \text{ (psec)}/86,400 \text{ (sec/day)}$$

$$= 1.1 \times 10^{-18} \quad (19)$$

over a 24-hour averaging time. Compare this to the stability of a hydrogen maser

$$df/f = 8 \times 10^{-16} \quad (20)$$

and it is apparent that the instability added by the fiber-optic cable due to temperature fluctuations is insignificant.

IX. Benefits to the DSN

Advanced fiber-optic systems based on these new developments could enable the final step toward a fully centralized SPC. They would enable transmission of microwave signals between the antenna cone and a nearby SPC. In the case of the receiver channel, this would permit removal of most of the equipment from the antenna cone area, resulting in a front-end area (FEA) configured as shown in Fig. 6. In this scheme, the RF-IF downconversion would be performed in a temperature-controlled and vibration-free environment at the SPC. Many of the advantages of the beam-waveguide antenna concept would be realized with this system, with the added advantage of a fully centralized SPC.

Also, the transmitter exciters could be centrally located in the fully centralized SPC for an entire Deep Space Communications Complex (DSCC). Since the exciter signal has a low dynamic range compared to the receiver channel, and operates on the same frequencies, a similar fiber-optic system could be used for both downlink and uplink. This would remove the exciter from the antenna cone, and preclude the need for stable frequency-determining elements in the antenna cone. Even the comb-generator calibration signals could be sent to the antenna cone from the SPC over these highly stable fiber links. Frequency stability and station flexibility could be enhanced by colocation of sensitive frequency determining elements in the SPC.

DSN engineers who design equipment for service in the antenna cone are well aware that the harsh operating environment limits system performance. A few of the ways in which the proposed fiber-optic links would impact the performance of the downlink are:

(1) Temperature control—Thermal control of the RF-IF chain could be substantially improved by relocating these components to the SPC, thereby reducing drift and noise.

(2) Vibration—The antenna cone is subjected to vibrations due to wind and other sources, which seriously impact frequency-determining elements such as quartz-crystal-oscillator-controlled phase-locked-loops by introducing close-to-carrier phase noise.

(3) Magnetic field shielding—The deleterious effects of magnetic fields from power supplies on the maser LNA and other sensitive components would be eliminated.

(4) Ease of servicing equipment—With the entire RF-IF chain located on the ground in the SPC, maintenance and servicing would no longer require technicians to climb the antenna; the only receiver components left in the antenna cone would be the LNA and the electro-optic modulator.

Bringing together the microwave signals from all of the antennas at the SPC opens the possibility of coherent uplink and downlink antenna arraying using any number of antennas in any configuration in real time. Novel radio science experiments utilizing the raw microwave signals from widely separated antennas will become possible. Upgrades to the receiver channels will be simplified greatly, since the raw microwave output of the LNAs will be available at the SPC. As newer and better receivers become available, they may be incorporated into the SPC with ease; no modifications to the front-end area would be required.

The central frequency and timing facility, the central monitor and control facility, and the central signal processing facility located at the fully centralized SPC could be extended to cover all stations at a complex regardless of their location. The central communications facility might also be located at the SPC, where all of the monitor and control signals are accessible. This would provide a convenient interface through which the complex could be controlled from a remote location such as JPL, via the existing international digital fiber-optic networks.

X. Summary of Concerns and Future Investigations

As may be expected, during the course of this preliminary study many questions were raised. These concerns are summarized here:

(1) Due to lack of time and equipment, the phase and amplitude linearity of the intensity modulators was not characterized. It may be the case that a microwave impedance-matching network for the optical modulator will be required to achieve sufficient phase and amplitude linearity in the microwave passband to meet DSN requirements. However, since the percentage bandwidth required is small compared to the carrier frequency (500 MHz/2.4 GHz = 20 percent at S-band, 6 percent at X-band), it is felt that good microwave design can provide a modulator with sufficient phase and amplitude linearity for DSN applications.

(2) The mean time to failure of the semiconductor-laser-pump diodes must be increased to an adequate level, or a multiple-pump scheme implemented to enable a soft failure-mode system. The laser manufacturers are already working on this problem for space-qualified systems.

(3) The improvement in the downlink stability budget when the RF-IF conversion is moved to the SPC must be quantified.

(4) The effect of the Nd:YAG laser linewidth on the microwave signal transmission on optical fiber for long distances (10s of kilometers) is not yet fully modeled. Preliminary calculations indicate that the bandwidth of the present optical fiber is adequate. If it is not, optical dispersion compensation schemes can be employed to increase bandwidth.

(5) The impact of laser wavelength stability on the stability performance of the fiber-optic system must be determined.

XI. Conclusion

This article presented a system design, analytical model, and experimental test data for a novel fiber-optic system for microwave analog signal transmission. Laboratory experiments matched the predicted values extremely well, indicating that such a system is capable of dynamic range approaching 150 dB-Hz, with frequency response to 18 GHz. The dynamic range of the maser and HEMT LNA outputs of a DSN antenna were calculated from the DSN specifications, and it was shown that the fiber-optic system described has adequate dynamic range and phase stability to transmit the S-band and X-band outputs of the maser or HEMT LNA to a remote SPC several kilometers away without appreciable degradation of signal quality. This system would also be capable of transmitting the exciter signals from a fully centralized SPC to the various antennas. The phase and amplitude linearity of the fiber-optic system in the S- and X-band passbands may be inadequate at present, and should be studied in the course of continuing research. From this preliminary study, however, it is clear that the basic building blocks are in place to realize a fully centralized SPC, and that fiber optics is the enabling technology to achieve this goal.

These advanced fiber-optic systems could substantially simplify the uplink and downlink channels of the DSN, and drastically increase the flexibility and capabilities of the DSN. This idea takes the concept of the beam-waveguide antenna one step further, by not only locating most of the signal processing equipment in a controlled environment, but more importantly, by bringing together the microwave outputs from the front ends of widely separated antennas to a fully centralized SPC. This capability would enable radical changes in DSN configurations, including the possibility of coherent uplink and downlink arraying and novel radio-science experiments utilizing the raw microwave signals from widely separated antennas in real time. The fully centralized SPC could itself be remotely controlled via the international digital fiber-optic networks already in place, enabling command and control of the DSN from JPL, or any other place.

References

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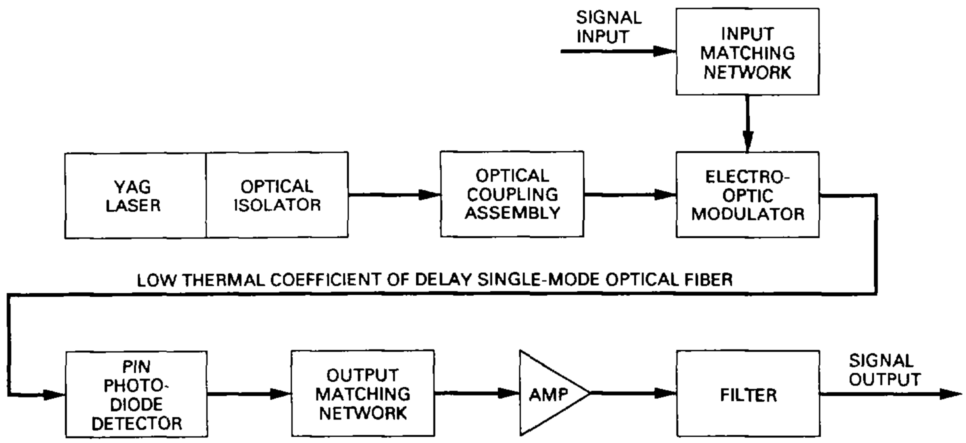

Fig. 1. Block diagram of proposed fiber-optic system.

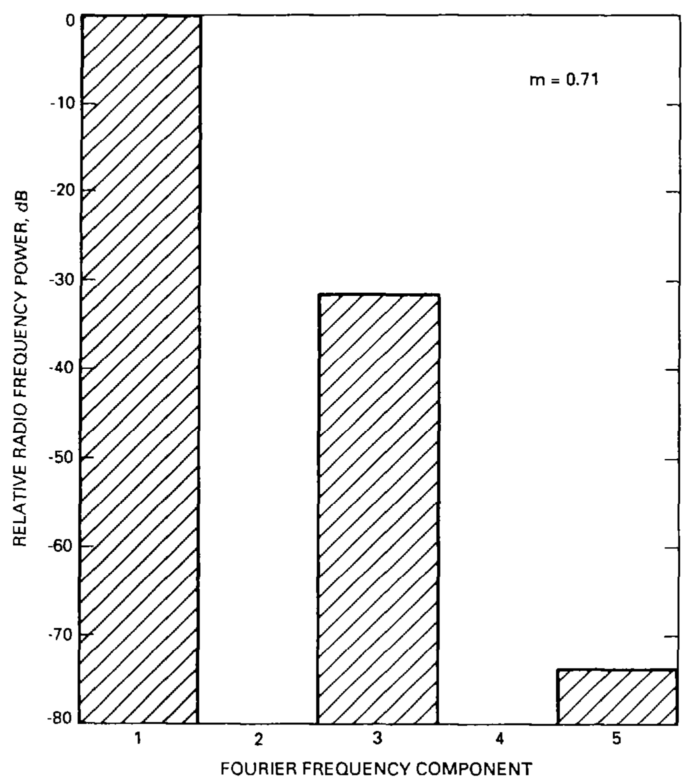

Fig. 2. Calculated fast Fourier transform of electro-optic modulator response: 71 percent modulation index.

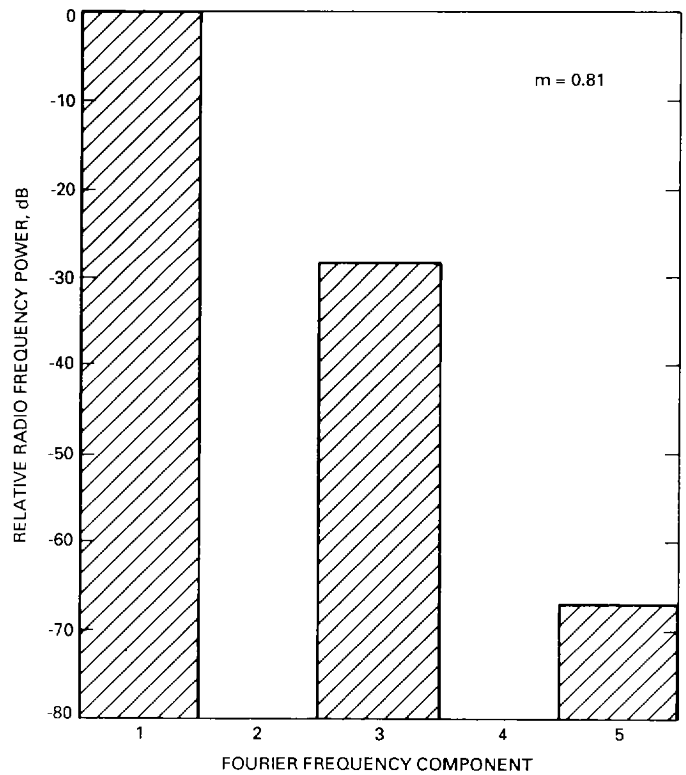

Fig. 3. Calculated fast Fourier transform of electro-optic modulator response: 81 percent modulation index.

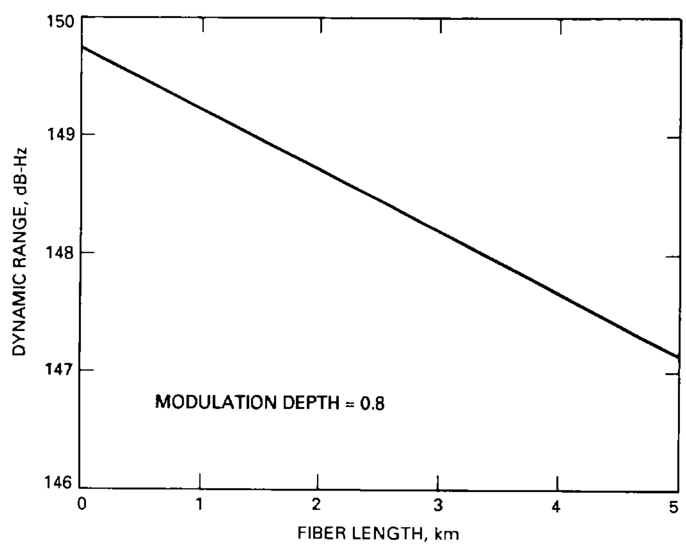

Fig. 4. Calculated fiber-optic system dynamic range versus fiber length.

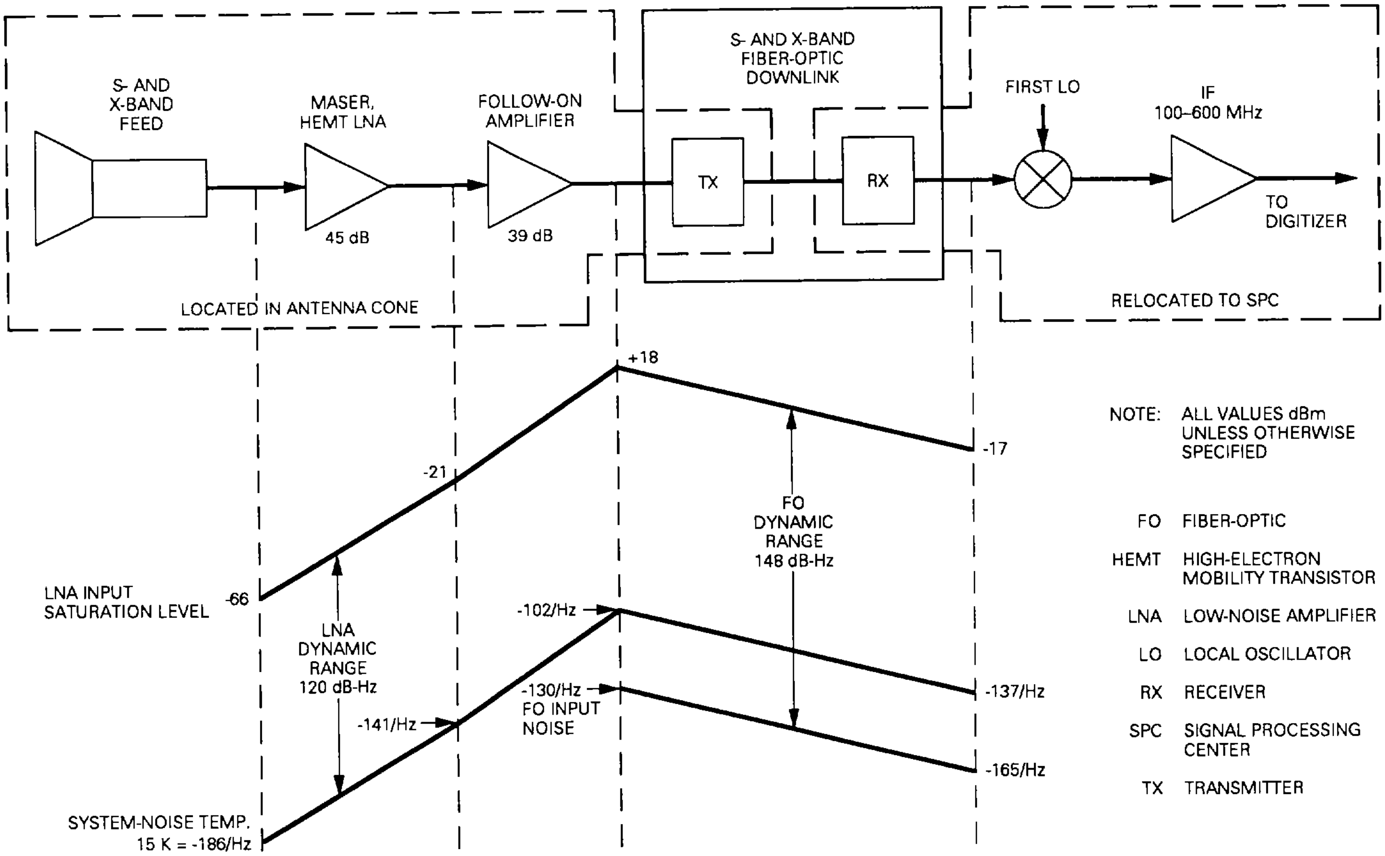

Fig. 5. Signal and noise levels of fiber-optic link for transmission of low-noise amplifier output.

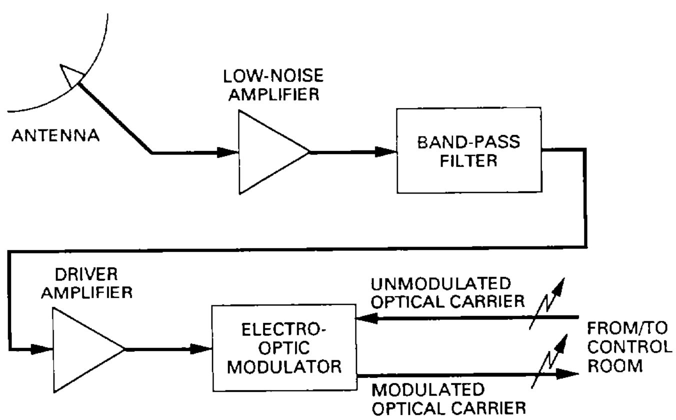

Fig. 6. New Deep Space Network front-end area configuration possible using advanced fiber optic links.